EXPERIMENTAL STUDY OF TURBULENT DIAMAGNETISM IN LIQUID SODIUM FLOW

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Abstract : The magnetic field suppression by strong turbulent flow of liquid sodium is studied experimentally in a nonstationary turbulent flow under moderate magnetic Reynolds number Rm > 10. The applied magnetic field is collinear to the streamline of the large-scale mean flow, what excludes the induction effects by the mean flow and the contribution of the turbulent diffusion. We show that during the highly turbulent stage of flow evolution the *mean* magnetic field is reduced by a factor of 0.6. The observed effect can be explained as the result of turbulent diamagnetism described by the term curl **(g×B)** in the mean-field induction equation (here **g** is the gradient of the energy of turbulent fluctuations and **B** is the mean magnetic field).

1. Introduction

The intensive small-scale turbulence in electroconducting fluids provides a variety of induction effects, described by about 20 terms in the general form of mean electromotive force [1]. Very few among them have been isolated and studied in detail. For laboratory study it is a hard problem to provide a MHD configuration which permits to separate the contribution of different effects. In our talk, we present results of laboratory study of the magnetic field suppression in the domain of strong turbulent fluctuations. We perform series of experiments with a nonstationary turbulent flow of liquid sodium, generated in a fast rotating toroidal channel after its abrupt braking. We applied the stationary curl-free magnetic field which is collinear to the streamline of the large-scale mean flow. This excludes an induction effects by the mean flow and the contribution of effective diffusion (the so-called beta-effect).

2. Experimental setup

We study spin-down flows of liquid sodium in a toroidal channel made of titanium alloy [2]. The torus has the radius R = 0.18m and the radius of the channel cross-section r_0 = 0.08 m. The rotation frequency of the channel is up to 50 rps, and the flow in the channel is generated by abrupt braking. The braking time does not exceed 0.3 s. The flow velocity reaches a maximum after the channel stops, and in the case of the free channel its toroidal component constitutes almost 70% of the linear velocity of the channel before braking. This means that the Reynolds number $Re = V\cdot r_0/\upsilon$ increases to $Re \approx 3\cdot 10^6$ at the most, which corresponds to the magnetic Reynolds number Rm ≈ 30.

For velocity measurements, we use a 2-axis local probe [3]. One of probe axis is oriented in azimuthal direction of clockwise channel rotation (toroidal) and its other axis oriented in radial direction (poloidal). At the first stage of braking the toroidal velocity of the fluid with respect to the halting vessel increases (as the probe is attached to the vessel, the measurement is performed in this initially moving frame of reference, and the initial zero value of the fluid velocity corresponds to solid body rotation). The maximum of the toroidal fluid velocity is reached as the vessel stops, and the subsequent dynamics is measured in the frame at rest. In this process, a transverse (poloidal) velocity has been developed. The corresponding variations of the toroidal and poloidal velocities, averaged over 20 runs are shown in Fig.2. The generation of poloidal velocity is provided by the curved channel and becomes more effective with increasing "thickness" of the torus [4]. For the maximal rotation rate, $\Omega = 50$ rps, at the end of braking the ratio of poloidal to toroidal mean velocities reaches $U^{pol} / U^{tor} = 0.18$. The maximal toroidal velocity $U^{tor} = 0.69\ V_0 = 39$ m/s, where V_0 is the velocity of the sodium on the channel axis before the brake. For details, refer to [3].

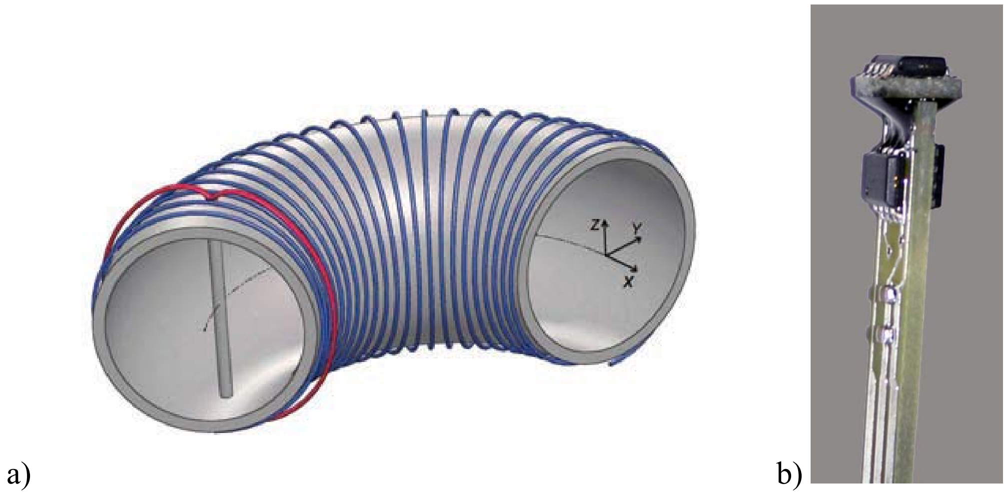

Figure 1: a) schematic of the toroidal channel; b) 3-component magnetic field probe.

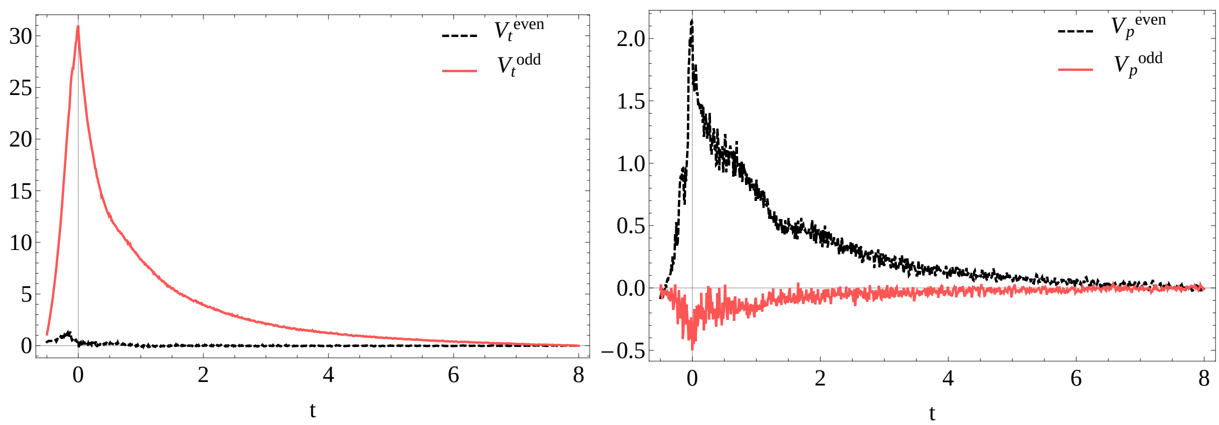

Figure 2: Evolution of mean toroidal (left) and poloidal (right) velocity for Ω = 40?? rps Red line corresponds to a half the sum and black one is a half the difference of measurements, obtained by clockwise and counterclockwise rotation of torus.

A coil, wound around the channel, is supplied by stabilized direct current and produces the toroidal field $B_T \approx 4$G (at the channel centerline). A tube of diameter 10 mm, crosses the channel parallel to the axis of rotation (Fig.1a) and located at the channel cross-section opposite to the position of the velocity probe. This tube can be used separately for local and integral magnetic field measurements. We measure three components of the local induced magnetic field **b** by a 3D Hall probe (see Fig.1b), constructed on Sentron's CSA-1V chips with 300 V/T magnetic sensitivity. The probe can move in the tube and can be fixed at the desired coordinate z.

To obtain integral magnetic field properties the same tube can be used to wound additional measuring coils, embracing two halves of channel’s cross-section (shown by red in

Fig.1). Coil's signal describes the change of internal magnetic flux as U= –dΦ/dt. This signal is being amplified using low noise voltage preamplifier SR560 (Stanford Research Systems, Inc., Sunnyvale, USA).

3. Characteristics of magnetic field

To obtain mean and statistical properties of local magnetic field 11 experiments for each magnetic probe position and rotation direction are made. To recoup external magnetic field influence one more series was performed with $B_T = 0$. Evolution of b_X and b_Z for several probe's coordinates is shown on Fig.3. t=0 corresponds to the beginning of braking. Coordinate z shows the position of the probe in the tube: z=0 corresponds to central position in the torus' cross-section, z=±80 are left- and right most possible positions in the tube.

Upper panels in Fig.3 show the even part of the magnetic field (the half-sum of signals, obtained for opposite direction of channel rotation) and lower panels show the odd component with respect to the direction of rotation. The main effect of magnetic field suppression is clearly seen in the B_X component. This can be explained as displacement of magnetic field from the turbulent core to the outer part of the channel cross-section. Some nonuniformities of magnetic field can be seen on B_Z graph.

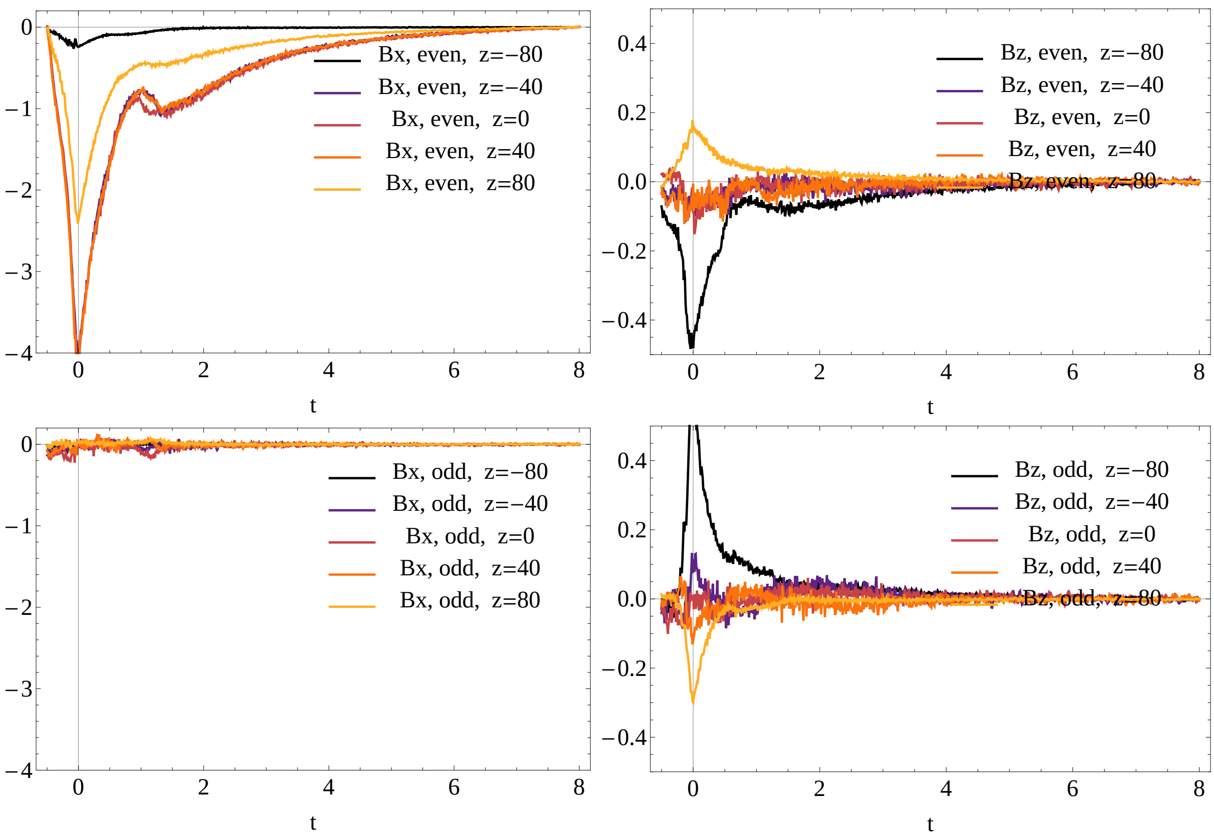

Figure 3: Local magnetic field evolution in several points along z-axis. Upper graphs correspond to a half-sum and lower ones show the half-difference of measurements, obtained by clockwise and counterclockwise rotation of torus.

Putting maximal values of longitudinal magnetic field component suppression for each probe's position allows us to restore the distribution of magnetic field along the z axis in the cross-section of the torus (see Fig.4). From integral measurements we can see the conservation of total magnetic flux in the cross-section of the coil. It means that the magnetic field is partially displaced to the channel periphery, where the B_z field should increase. We do not observe any increase, thus the fields should be shifted into the walls.

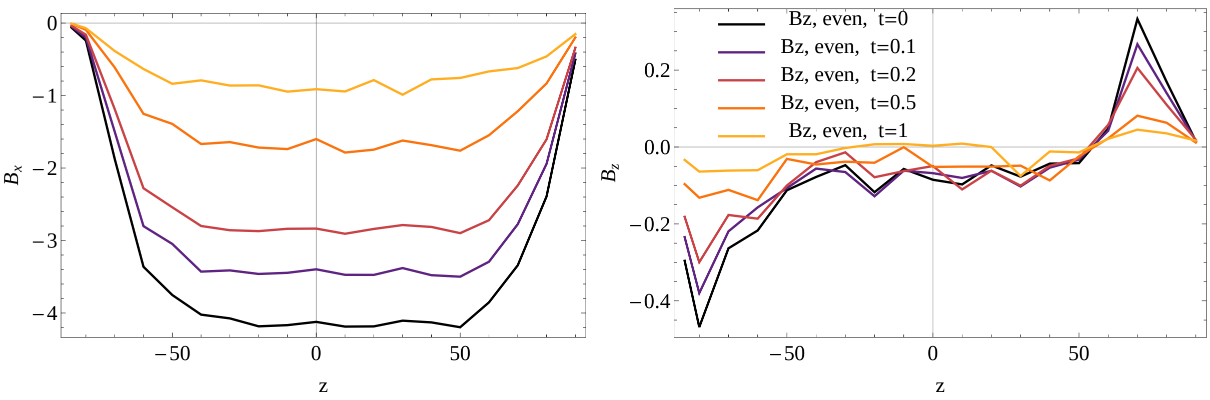

Figure 4: Profiles of local magnetic field components for several time intervals from the beginning of breaking with constant component subtracted.

Comparison of graphs from Fig.5 gives information about the origin of magnetic field displacement. Evolutions of magnetic field fluctuations follows the evolution of energy of velocity pulsations, which are caused by the turbulence.

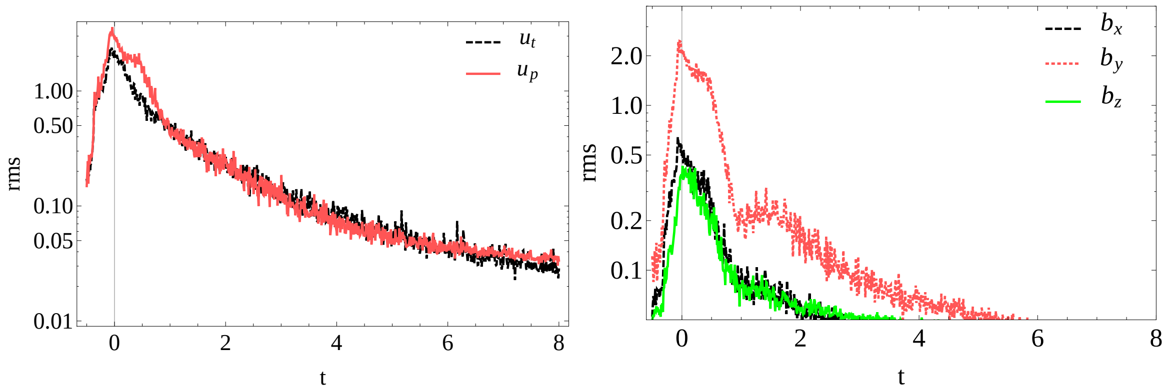

Figure 5: Fluctuating part of the torodal and poloidal velocity (left) and of local magnetic field components (right).

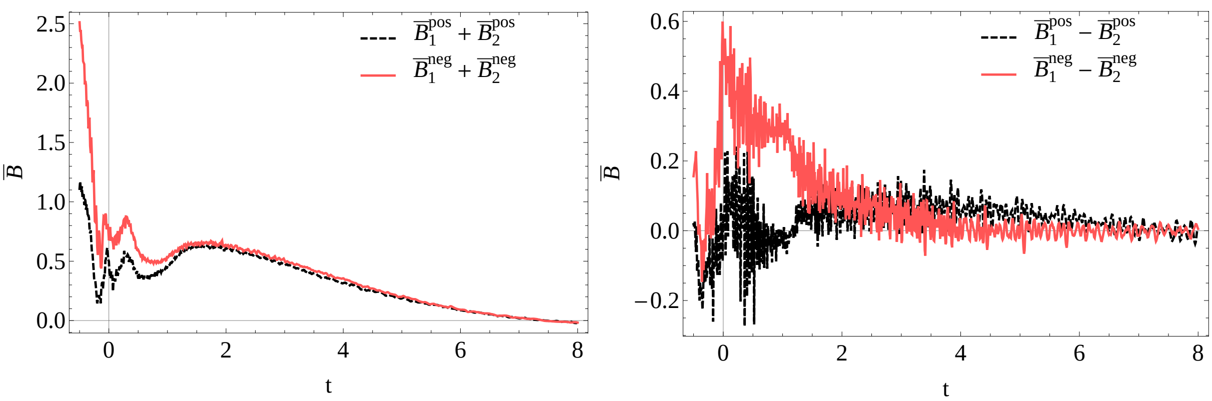

Figure 6: Sum (left) and difference (right) of measurements obtained by measuring coils. Dashed line and solid line correspond to clockwise and counterclockwise rotation of torus, respectively.

Local measurements do not provide the whole information about distribution of the magnetic field for clear interpretation. Integral measurements of magnetic flux can support our guess about the turbulent diamagnetic effect responsible for magnetic field dump in the turbulent flow. Mean field theory suggest that magnetic field must be pushed from intensive turbulence to more quiet regions. In our case it means that the magnetic fields can be transported to the border of the channel or even in the walls, therefore so that we do not observe an increase of magnetic field by local probes. Independent measurements of EMF in two coils allow us to estimate the averaged magnetic field over the channel half cross-sections (see fig. 6). First of all we do not observe significant change of the total magnetic flux along the channel. We explain an increase of 1 Gauss order as result of advection of inhomogeneous magnetic field near the wall caused by rough step of induction coil wings. This value is in agreement with measurements of B_z component due to same effect. The second interesting result we found in residual flux between two coils (right panel in Fig.6). We explain strong fluctuation as an effect of the Karman vortices generated by the stream flows around the tube installed in the channel. These vortices produced specific oscillations with frequency decaying as the ratio of the mean flow to radius of the tube.

4. Conclusion

Our measurements show that during the highly turbulent stage of flow evolution the *mean* magnetic field is reduced by a factor of 0.6. The observed effect can be explained as the result of turbulent diamagnetism described by the term curl ($\mathbf{g}\times\mathbf{B}$) in the mean-field induction equation (here $\mathbf{g}$ is the gradient of the energy of turbulent fluctuations and $\mathbf{B}$ is the mean magnetic field).

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5. References

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